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AN INVESTIGATION OF A THERMAL ICE-PREVENTION SYSTEM

FOR A C-46 CARGO AIRPLANE

V - EFFECT OF THERMAL SYSTEM ON

AIRPLANE CRUISE PERFORMANCE

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SUMMARY

As a part of a comprehensive investigation of a thermal ice-prevention system for a C-46 cargo airplane, flight tests have been conducted to evaluate the effect of the system upon the aerodynamic performance of the airplane. With the airplane operating at a cruise condition, the installation of the thermal ice-prevention system reduced the indicated airspeed by about 6 miles per hour, the equivalent of a loss of about 92 thrust horsepower. This loss in performance is attributed almost exclusively to the parasite drag of the heat-exchanger installations. The loss due to the internal drag of the thermal ice-prevention system and the loss due to the back pressure on the engines resulting from the heat exchangers is shown to be negligible.

INTRODUCTION

Previous researches relating to the prevention of ice formation upon the wings and empennage of aircraft have, in general, been directed toward the development of a practical thermal ice-prevention system which would enable the aircraft to operate safely and for prolonged periods in inclement weather. In view of the urgent need of such equipment, to permit the execution of tactical military operations regardless of weather, emphasis has been placed upon the development of a thermal system satisfactory from

the standpoint of ice prevention, and only superficial, if
any, attention has been given to the possible detrimental
effects of the system upon the aerodynamic performance of
the aircraft.

The purposes of the investigation reported herein,
which is a part of a comprehensive investigation of a ther-
mal ice-prevention system for a C-46 cargo airplane (refer-
ences 1 to 4), were (1) to determine the effect of the
thermal ice-prevention system upon the performance of the
C-46 airplane, (2) to establish, if possible, the factors
contributing to any change in performance, and (3) to
evaluate the amounts of such contributions. The investi-
gation was conducted on the C-46 airplane as successful
flights in natural-icing conditions (reference 4) have
established the suitability of the thermal ice-prevention
system installed in that airplane as a practical means of
ice prevention.

The investigation included flight tests, with the air-
plane operating at a cruise condition, to determine experi-
mentally the change in airplane performance resulting from
the installation of the thermal ice-prevention system.
Consideration was also given, experimentally and analytically,
to the determination of the contribution of the following
factors to the change in airplane performance: (1) the
increase in exhaust-gas back pressure resulting from the
heat exchangers, (2) the external drag of the heat-exchanger
installations, (3) the internal drag of the thermal ice-
prevention system, and (4) the weight of the thermal ice-
prevention system.

This research was conducted at the Ames Aeronautical
Laboratory as a part of a comprehensive investigation of the
thermal ice-prevention system of the C-46 airplane which was
initiated at the request of the Air Technical Service Command
of the U.S. Army Air Forces.

DESCRIPTION OF EQUIPMENT

Airplane

The C-46 cargo airplane utilized in this investigation
is a low-wing monoplane of the heavy military cargo type
(fig. 1). The following specifications of the C-46 airplane,
pertinent to this investigation, have been taken from ref-
erence 5:

Airplane
    Manufacturer . . . . Curtiss-Wright
    Type . . . . C-46, military-cargo
    Army number 41-12295
    Number of engines 2
    Length . . . . 77 ft 1 in.
    Wing span . . . . 108 ft 0 in.
    Over-all height (three-point position) . . . 22 ft 2 in.
    Wing area (including flaps and ailerons) . . 1360 sq ft
    Empty weight . . . . approx. 31,500 lb
    Gross weight (max. for take-off) . . . . 48,000 lb
    Gross weight (max. for landing) . . . . 46,000 lb

Engine
    Manufacturer . . . . Pratt & Whitney
    Type . . . . . . 18-cylinder, twin-row, radial, air-cooled
    Model number R-2800-51
    Engine-propeller gear ratio 2:1
    Engine-supercharger gear ratio (low blower). . . . 7.6:1
    Engine-supercharger gear ratio (high blower) . . . 9.9:1
    Compression ratio 6.7:1
    Bore . . . . 5.75 in.
    Stroke . . . . 6.00 in.
    Displacement . . . . 2804 cu in.
    Rating . . . . 2000 bhp at 2700 rpm
            for take-off (5 min only); 1600 bhp at 2400 rpm
            for maximum continuous emergency operation, S.L.
            to 5700 ft (Ratings based on 100-octane, amend-
                ment 5, performance grade No. 125 fuel)

Propeller
    Manufacturer . . . . Hamilton Standard
    Drawing number 6491A-0
    Number of blades 3
    Diameter . . . . 15 ft

Thermal Ice-Prevention Equipment

    The thermal ice-prevention equipment, as originally in-
stalled in the C-46 airplane and as revised for tests in
natural-icing conditions, is completely described in refer-
ences 3 and 4, respectively. For the investigation reported
herein the thermal ice-prevention system was in the revised
condition described in reference 4. The original heat-
exchanger installation for the C-46 airplane is shown in fig-
ure 2. Figure 3 shows the special fairings which were con-
structed and installed over the heat exchangers for a phase

of this investigation. Figure 4 shows a heat-exchanger in-
stallation replaced with a standard production exhaust stack.

Instrumentation

Calibrated standard instruments were installed in the
airplane to indicate engine manifold pressure, engine speed,
pressure altitude, and indicated airspeed. A shielded
mercury-in-glass thermometer, mounted outside the fuselage
at station 286, was used to indicate the ambient-air temper-
ature.

TESTS

The effect of the thermal ice-prevention system on the
performance of the airplane was measured in flight in terms
of indicated airspeed while maintaining constant manifold
pressure on the engines, and in terms of manifold pressure
while maintaining a constant indicated airspeed. All tests
were conducted at 10,000 feet density altitude, with the
engines operating at 1900 rpm and low blower, and at an air-
plane gross weight of approximately 38,000 pounds.

The tests were conducted under the following four oper-
ating conditions:

1. Heat exchangers in place, heated air discharged over-
        board, engine manifold pressure maintained con-
        stant at 30 inches of mercury

2. Heat exchangers in place, heated air delivered to
        the surface-heating system engine manifold pres-
        sure maintained constant at 30 inches of mercury

3. Heat exchangers removed, standard production exhaust
        stacks installed, engine manifold pressure main-
        tained constant at 30 inches of mercury

4. Heat exchangers removed, standard production exhaust
        stacks installed, indicated airspeed maintained
        constant at values previously established by
        tests of condition 1

These conditions provide the change in performance
caused by the thermal system in terms of airspeed (condi-

tions 1, 2, and 3) and in terms of manifold pressure (conditions 1, 2, and 4). The effect of the heat-exchanger fairings (fig. 3) upon the performance of the airplane was established by flights with the fairings in place and removed, with the airplane operating under conditions 1 and 2.

Data during each test were recorded manually at intervals of approximately 1 minute for a sufficient length of time after equilibrium conditions had been established to assure attainment of representative results.

RESULTS

The results of the flight tests are presented in table I. The values of ambient-air temperature, pressure altitude, and indicated airspeed listed in the table are the averages of the recorded data for each test condition. The variation of individual readings of these variables from the average values presented did not exceed ±1° F, ±50 feet, and ±3 miles per hour, respectively. The values of the ambient-air temperature have not been corrected for the effect of kinetic heating.

The indicated airspeeds obtained during the tests at conditions 1, 2, and 3 are presented in figure 5 as functions of pressure altitude. Since the relationship of indicated airspeed to pressure altitude for conditions 1 and 2 was substantially identical, only one curve has been drawn through the experimental points for those two conditions.

DISCUSSION

Over-All-Performance Change Resulting from
the Installation of the Thermal System

The results (table I and fig. 5) indicate that the performance change resulting from the installation of the thermal system amounted to approximately 6 miles per hour indicated airspeed or 1.4 inches of mercury manifold pressure at the test conditions.

Sufficient performance data are available for the C-46 cargo airplane to interpret these performance changes

in terms of brake horsepower. Figure 6 presents curves of indicated airspeed and manifold pressure as functions of brake horsepower which have been plotted from the data of reference 5. Although none of the curves of figure 6 are for the 10,000-foot density altitude test condition, the fact that the curves are parallel allows the assumption to be made that the curve for the test conditions would also have the same slope. Thus, calculations involving the change in brake horsepower for a given change in airspeed or manifold pressure can be made, using the slopes of the curves presented in figure 6.

The following derivation illustrates how the data of figure 6 were employed to evaluate the performance difference caused by the exchanger installations in terms of brake horsepower and, by assuming a propulsive efficiency, in terms of thrust horsepower:

η — propulsive efficiency (assumed to be constant for all test conditions)

$(thp)_1$ — thrust horsepower developed by the airplane in condition 1 $[(bhp)_1\eta]$

$(thp)_3$ — thrust horsepower developed by the airplane in condition 3 $[(bhp)_3\eta]$

$(thp)_4$ — thrust horsepower developed by the airplane in condition 4 $[(bhp)_4\eta]$

$(thp)_{b.p.}$ — thrust-horsepower reduction attributed to heat-exchanger exhaust-gas back pressure $[(bhp)_{b.p.}\eta]$

$(thp)_{int}$ — thrust-horsepower reduction attributed to internal drag of the thermal system $[(bhp)_{int}\eta]$

$(thp)_{ext}$ — thrust-horsepower reduction attributed to external drag of the thermal system $[(bhp)_{ext}\eta]$

Since the manifold pressure, engine speed, and density altitude are the same at conditions 1 and 3, the thrust horsepower developed by the airplane would be the same were it not for the effects of the heat-exchanger exhaust-gas back pressure when operating at condition 1. Thus,

$$(thp)_1 = (thp)_3 - (thp)_{b.p.}$$

or

$$(bhp)_i = (bhp)_3 - (bhp)_{b.p.} \tag{1}$$

It is also evident that the difference between the thrust horsepower developed by the airplane in conditions 1 and 4 is equivalent to the combined effects of the internal drag $(thp)_{int}$ and the external drag $(thp)_{ext}$. Thus,

$$(thp)_{int} + (thp)_{ext} = (thp)_1 - (thp)_4$$

or

$$(bhp)_{int} + (bhp)_{ext} = (bhp)_1 - (bhp)_4 \tag{2}$$

Equations (1) and (2) may be combined to yield the following relationship:

$$(thp)_{b.p.} + (thp)_{int} + (thp)_{ext} = (thp)_3 - (thp)_4$$

or

$$(bhp)_{b.p.} + (bhp)_{int} + (bhp)_{ext} = (bhp)_3 - (bhp)_4 \tag{3}$$

Thus the sum of the power losses caused by the exchanger installations is equivalent to the difference in power required to operate at conditions 3 and 4. The brake-horsepower loss $[(bhp)_3 - (bhp)_4]$ may be evaluated from figure 6 for either the manifold-pressure difference or the airspeed difference between conditions 3 and 4. In the following calculations, the brake horsepower is determined by both methods.

1. Horsepower loss computed from airspeed data.- From table I the average airspeeds for conditions 3 and 4 may be taken as 169 and 163 miles per hour, respectively. The brake horsepower for these airspeeds (curve 1, fig. 6(a)) corresponds to 810 and 750 brake horsepower. Therefore,

$$(bhp)_3 - (bhp)_4 = 810 - 750$$

$$= 60 \text{ brakehorsepower per engine, or}$$

$$120 \text{ brake horsepower for the airplane}$$

and, assuming a propulsive efficiency of 0.8

$$(thp)_{b.p.} + (thp)_{int} + (thp)_{ext} = 0.8 \times 120$$

$$= 96 \text{ thrust horsepower total}$$

2. Horsepower loss computed from manifold-pressure data.
From table I the manifold pressures at conditions 3 and
4 were 30 and 28.6 inches of mercury, respectively.
Therefore, from figure 6(b), curve 3, $(bhp)_3 = 900$ and
$(bhp)_4 = 845$. Therefore,

$$(bhp)_{b.p.} + (bhp)_{int} + (bhp)_{ext}$$

$$= 900 - 845$$

$$= 55 \text{ brake horsepower per engine, or}$$

$$110 \text{ brake horsepower for the airplane}$$

and

$$(thp)_{b.p.} + (thp)_{int} + (thp)_{ext} = (110)(0.8)$$

$$= 88 \text{ thrust horsepower total}$$

The experimental data for methods 1 and 2 were taken in-
dependently of each other, and the methods provide reasonable
agreement. Therefore, the performance change in terms of
thrust horsepower caused by the installation of the thermal
system will be taken as 92 thrust horsepower, which is an
average of the values obtained by the above two methods.

Reduction of Power Attributed to Heat-Exchanger

Exhaust-Gas Back Pressure

An estimate of the reduction of power caused by the
heat-exchanger exhaust-gas back pressure may be made on the
basis of general data available. The effects of back pres-
sure on a Fiat two-row, 18-cylinder, air-cooled, 1000-
horsepower engine, type A80-RC-41, when operated at constant
manifold pressure and carburetor-air temperature are given
in reference 6 in terms of atmospheric pressure as follows:

$$(bhp)_a = (bhp)_s \left(1 + \frac{\Delta P}{K}\right)$$

where

$(bhp)_a$ brake horsepower at 59° F carburetor-air temperature

$(bhp)_s$ brake horsepower at standard sea-level atmospheric
            conditions

ΔP atmospheric-pressure difference between sea level
            and the atmospheric pressure at which $(bhp)_a$
            is desired, millimeters of mercury

K constant dependent on manifold pressure

       If it is assumed that the Pratt and Whitney R-2800 en-
gines employed in the C-46 airplane are similar to the Fiat
engine with regard to back-pressure effects, the effects of
the back pressure caused by the heat-exchanger installations
on the C-46 cargo airplane may be calculated. The exhaust-
gas pressure drop through the left outboard heat exchanger
has been measured to be approximately 0.5 to 0.7 inch of
mercury at the test conditions. If the value of 0.7 and the
value of K (3500) taken from reference 6 for 30 inches of
mercury manifold pressure is used, the effect of the heat
exchangers at the 8000-foot pressure-altitude test condi-
tions is about 5 brake horsepower per engine or 8 thrust
horsepower for the airplane.

       Reference 7 provides the following general relationship
for constant-boost operation of an aircraft engine for small
changes in atmospheric pressure and temperature:

$$(bhp) \propto p^{-0.1} \, T^{-0.8}$$

where

p   atmospheric pressure, absolute

T   atmospheric temperature, absolute

The exponential values of -0.1 and -0.8 are the mean values
given by reference 7. Thus, for the 8000-foot pressure-
altitude test conditions, since brake horsepower varies as
$p^{-0.1}$, the effect of the heat-exchanger back pressure is
about 4 brake horsepower per engine or 6.4 thrust horsepower
for the airplane.

Either of the values of thrust—horsepower reduction
attributed to exhaust—gas back pressure, as derived from the
relationships given in reference 6 or 7, is not more than
0.6 percent of the total power developed by the engines, and
would cause a decrease in indicated airspeed of about one—
half mile per hour (fig. 6).

Reduction of Power Attributed to the Internal Drag

of the Thermal System

As indicated in table I and figure 5, there was no meas—
urable difference between the performance of the airplane
when the heated air was discharged (condition 1) and when the
heated air was delivered into the surface—heating system
(condition 2).

If it is assumed, in either case of operation, that the
same amount of air enters the heat exchangers and all the
kinetic energy of the air is expended, a maximum value of
$(thp)_{int}$ may be calculated. From the data of reference 4,
the heated—air flow rate through all the heat exchangers at
the 8000—foot pressure—altitude conditions may be approxi—
mated as 14,000 pounds of air per hour. The indicated air—
speed, given in figure 5, for this condition is 163 miles
per hour and the total kinetic energy of the 14,000 pounds
of air per hour would amount to about $8\frac{1}{2}$ thrust horsepower.
In any actual case, the horsepower loss caused by internal
drag would be less.

Reduction of Power Attributed to the External Drag

of the Thermal System

It has been established that the exhaust—gas back pres—
sure and the internal—drag effects of the thermal system
contribute only slightly to the total performance difference
measured. These effects are estimated to total less than 15
thrust horsepower. The remainder, approximately 77 thrust
horsepower, is attributed to the external drag of the heat—
exchanger installations. It is evident from figure 2 that
the external drag would be large, and it is evident from the
test results (table I) that the fairings (fig. 3) had no
measurable beneficial effect.

Considerable external drag, however, is not necessarily inherent to heat—exchanger installations. If the heat exchangers were located within the nacelles and the air—inlet scoops located in the stagnation region of the cowling, the external drag could be reduced considerably. The installation on the C—46 airplane was installed for the purpose of investigating the surface—heating system, and the available time was not sufficient to permit complicated nacelle alterations to be made for submerging the exchangers within the nacelles.

Additional Airplane Gross Weight Attributed

to the Thermal System

The performance tests were all conducted with the airplane at approximately the same weight and, therefore, the test measurements did not include data on the effects of the additional weight contributed to the airplane by the thermal system.

Based on weight studies made of previous thermal systems similar to that installed in the C—46 cargo airplane, the weight added to the bare airplane (i.e., without any form of ice—prevention equipment) by the installation of the thermal system has been approximated to be 500 pounds. The 1900—rpm cruise charts of reference 5 indicate that at 8000 feet pressure altitude, and a constant manifold pressure of 30.2 inches of mercury, a change in airplane gross weight from 35,000 to 40,000 pounds (an increase in weight equal to 10 times the estimated weight of the thermal system) produces a corresponding change in indicated airspeed of 2 miles per hour. Thus, the installation weight evidently has a negligible effect on the performance of the airplane at the test conditions.

The additional fuel weight which must be carried by the airplane at the test conditions to overcome the effects of the heat—exchanger installations may be calculated as follows:

At the 8000—foot pressure—altitude 163—miles—per—hour test conditions (conditions 1 and 4), the additional power required to overcome the effects of the heat—exchanger installations is $(bhp)_1 - (bhp)_4$. The difference in power required at conditions 3 and 4 $[(bhp)_3 - (bhp)_4]$ has been evaluated as about 115 brake horsepower, or about 57

brake horsepower per engine. Also, by equation (1),
$(bhp)_3 - (bhp)_{b.p.} = (bhp)_1$. Thus, neglecting the back-
pressure effects, the horsepower difference $[(bhp)_1 - (bhp)_4]$
may be taken as 57 brake horsepower per engine. Figure 7
presents airplane fuel consumption as a function of brake
horsepower and has been plotted from data given in reference
5. From figure 7, for the power range employed in the tests,
it is evident that a brake-horsepower difference of 57 brake
horsepower causes an increased fuel consumption of about
7 gallons per hour or about 45 pounds of fuel per hour. This
value would be slightly less if the effects of $(bhp)_{b.p.}$
were considered.

CONCLUSIONS

1. The performance change resulting from the installa-
tion of the thermal system in the C-46 cargo airplane amounted
to approximately 6 miles per hour indicated airspeed or 92
thrust horsepower at the 10,000-foot density-altitude test
conditions.

2. The performance change resulting from the installa-
tion of the thermal system in the C-46 airplane is almost
entirely due to the parasite drag of the heat-exchanger in-
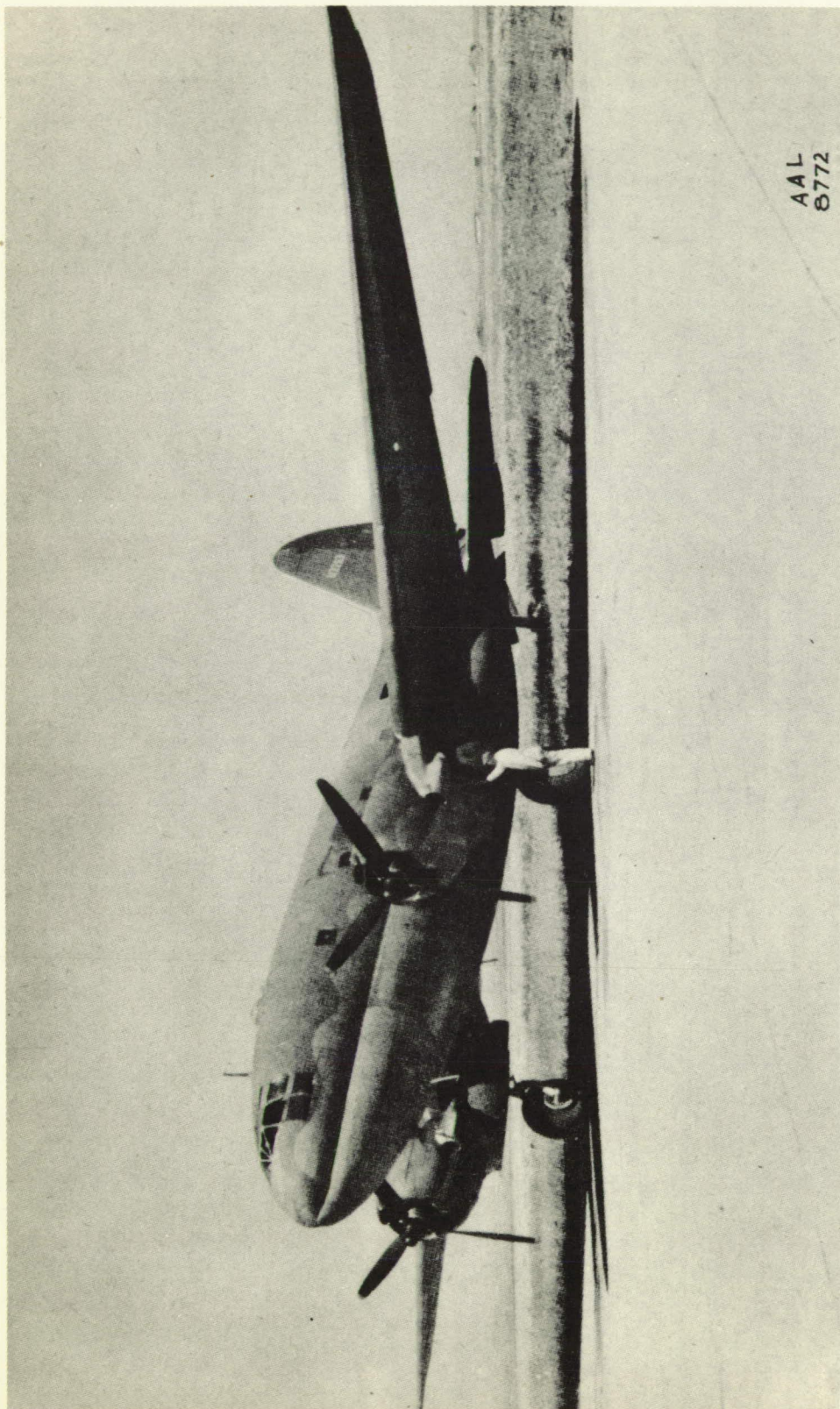stallations.

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    National Advisory Committee for Aeronautics,
        Moffett Field, Calif.

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TABLE I.- EFFECT OF THERMAL ICE-PREVENTION SYSTEM ON THE
PERFORMANCE OF THE CURTISS-WRIGHT C-46 CARGO AIRPLANE

Flight number	Run number	Test duration (min)	Average ambient-air temperature (°F)	Engine manifold pressure (in.Hg)	Engine speed (rpm)	Average pressure altitude (ft)	Average air density (slugs per cu ft)	Average corrected indicated airspeed (mph)	Exchangers with fairing in place	Operating condition
88	1	17	42	30.0	1900	9010	0.00175	165	Inboard	(1) Heat exchangers in place. Heated air discharged.
89	1	18	59	30.0	1900	8000	.00176	160	Inboard	
90	1	18	62	30.0	1900	7810	.00176	163	Inboard	
91	1	14	56	30.0	1900	8300	.00175	164	Inboard	
92	2	9	62	30.0	1900	8010	.00175	164	Inboard	
101	1	10	56	30.0	1900	8400	.00175	164	None	
102	1	20	61	30.0	1900	8000	.00176	162	All	
90	2	5	62	30.0	1900	7810	.00176	162	Inboard	(2) Heat exchangers in place. Heated air delivered into surface heating system.
91	2	5	56	30.0	1900	8300	.00175	163	Inboard	
92	1	11	61	30.0	1900	7990	.00176	164	Inboard	
101	2	10	56	30.0	1900	8400	.00175	163	None	
102	2	10	62	30.0	1900	8000	.00176	162	All	
96	1	20	64	30.0	1900	8050	.00174	168		(3) Heat exchangers removed. Manifold pressures same as for (1) and (2).
96B	1	20	64	30.0	1900	7910	.00175	169		
97	1	20	53	30.0	1900	8400	.00176	169		
97B	1	20	54	30.0	1900	8300	.00176	169		
98	1	20	55	30.0	1900	8500	.00175	169		
98B	1	20	55	30.0	1900	8300	.00176	168		
97B	2	8	53	28.5	1900	8300	.00176	163		(4) Heat exchangers removed. Indicated airspeed same as (1) and (2).
98	2	10	55	28.8	1900	8500	.00175	164		
98B	2	10	56	28.5	1900	8280	.00176	163		

Figure 1.- The Curtiss-Wright C-46 cargo airplane for which the NACA designed and installed thermal ice-prevention equipment.
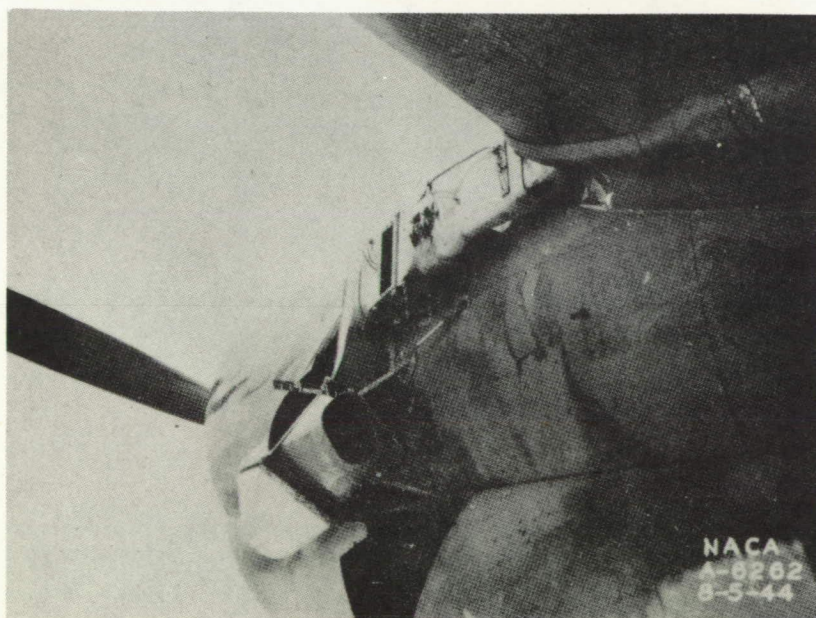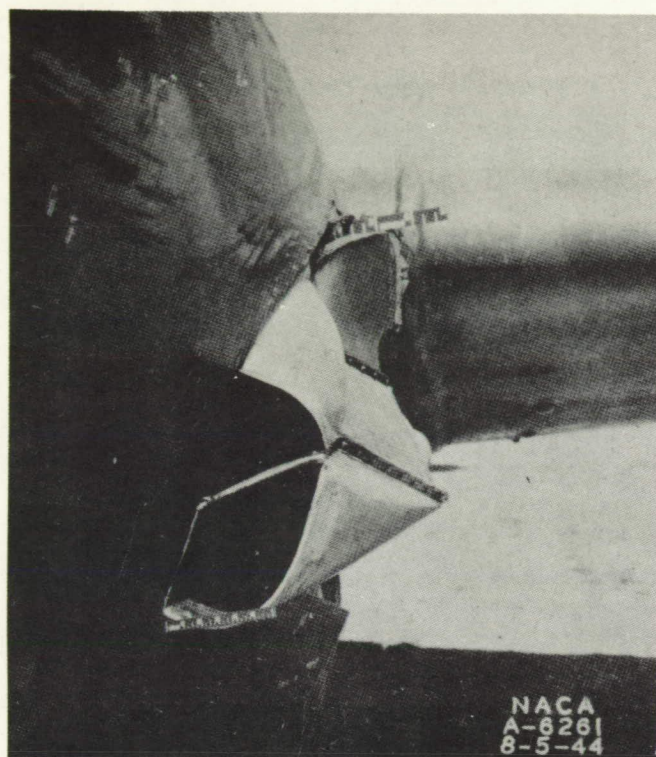
Figure 2.- Two views of typical heat-exchanger installation,
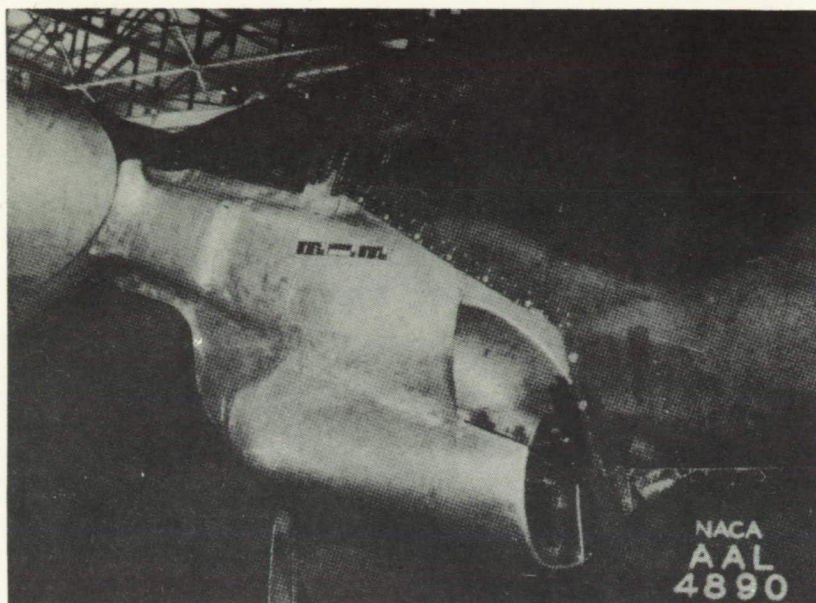   without fairing, on the Curtiss-Wright C-46
cargo airplane.

Figure 3.- Typical heat-exchanger installation, with fairing,
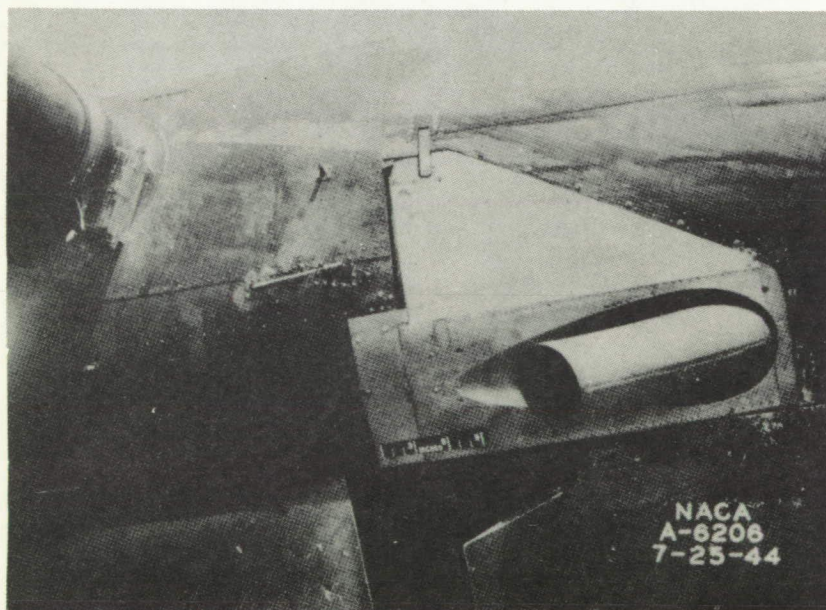on the Curtiss-Wright C-46 cargo airplane.

Figure 4.- View showing standard production exhaust stack on
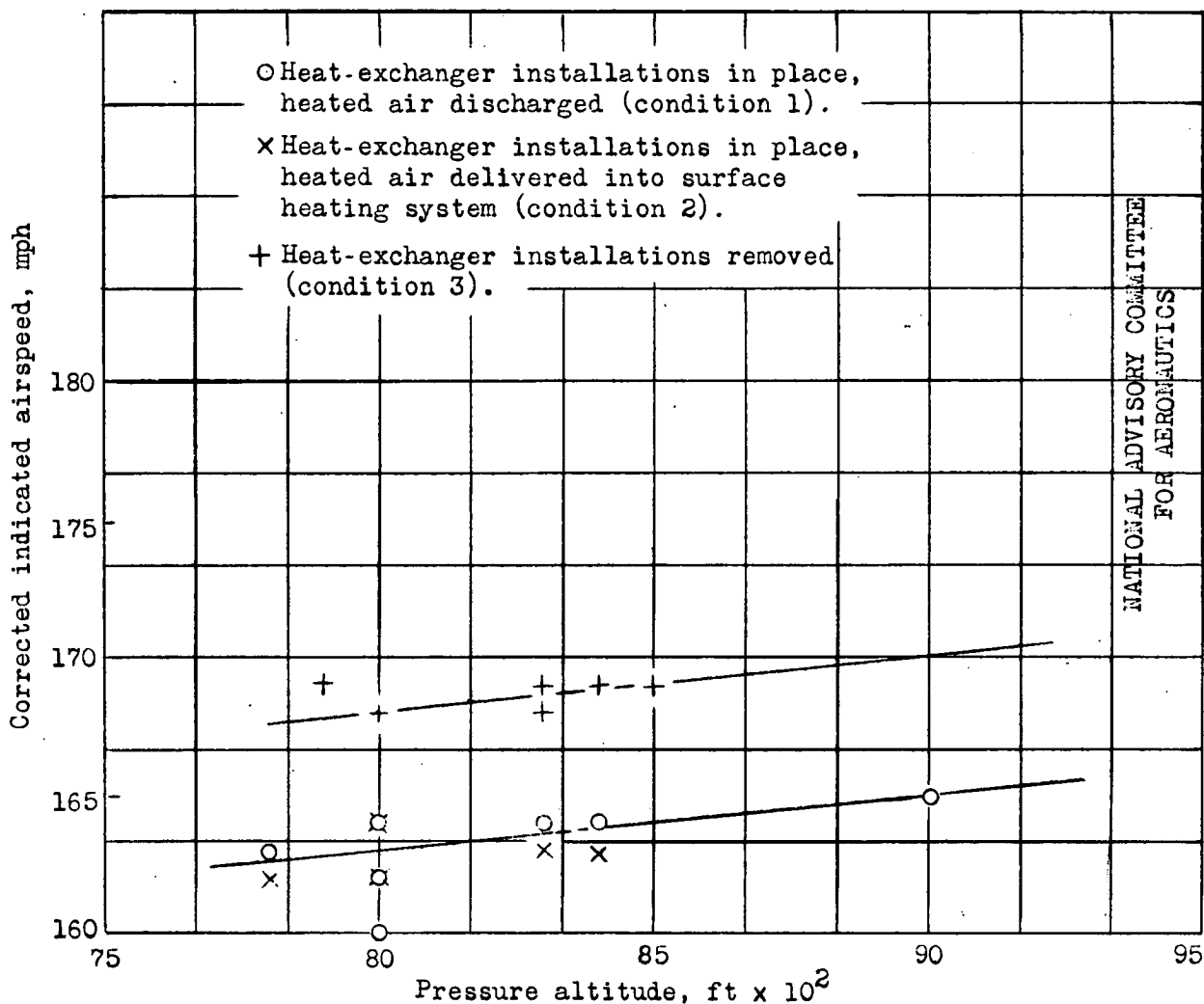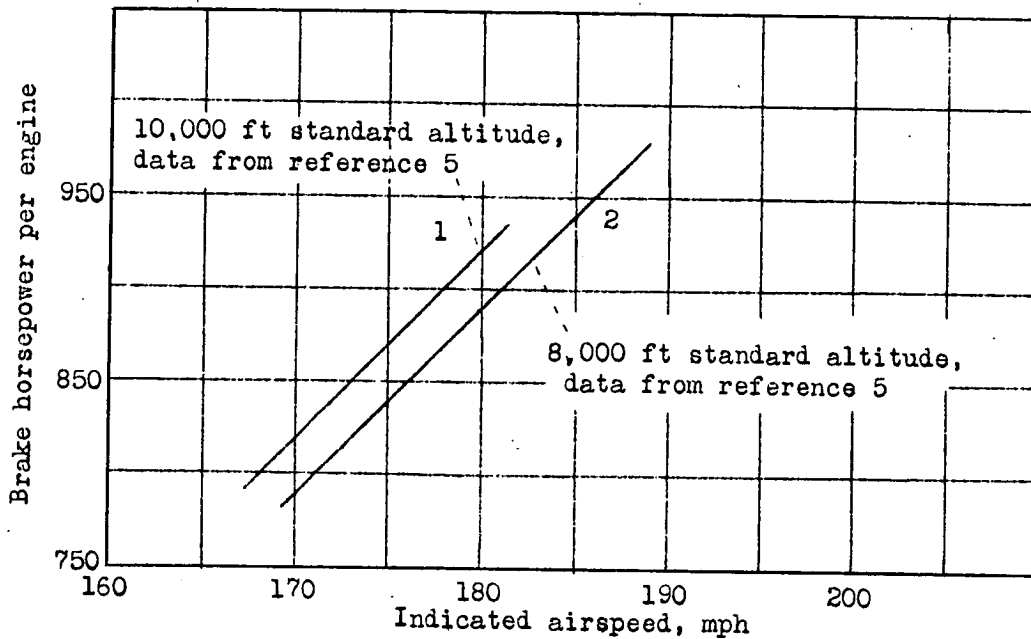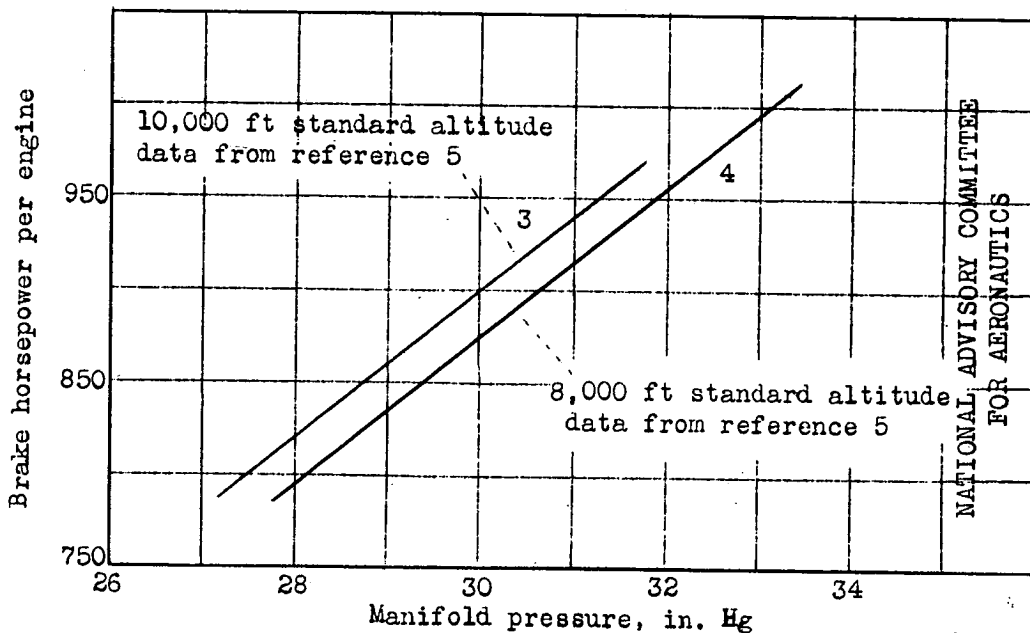the Curtiss-Wright C-46 cargo airplane.

Figure 5.- Variation of indicated airspeed with pressure altitude for the Curtiss-Wright C-46 cargo airplane with and without the heat-exchanger installations in place. Flight conditions: 10,000 feet density altitude; 30 inches of mercury manifold pressure and 1900 rpm.

(a) Brake horsepower as a function of
    indicated airspeed.

(b) Brake horsepower as a function of
    manifold pressure.

Figure 6.- 1900 rpm performance curves for Curtiss-Wright
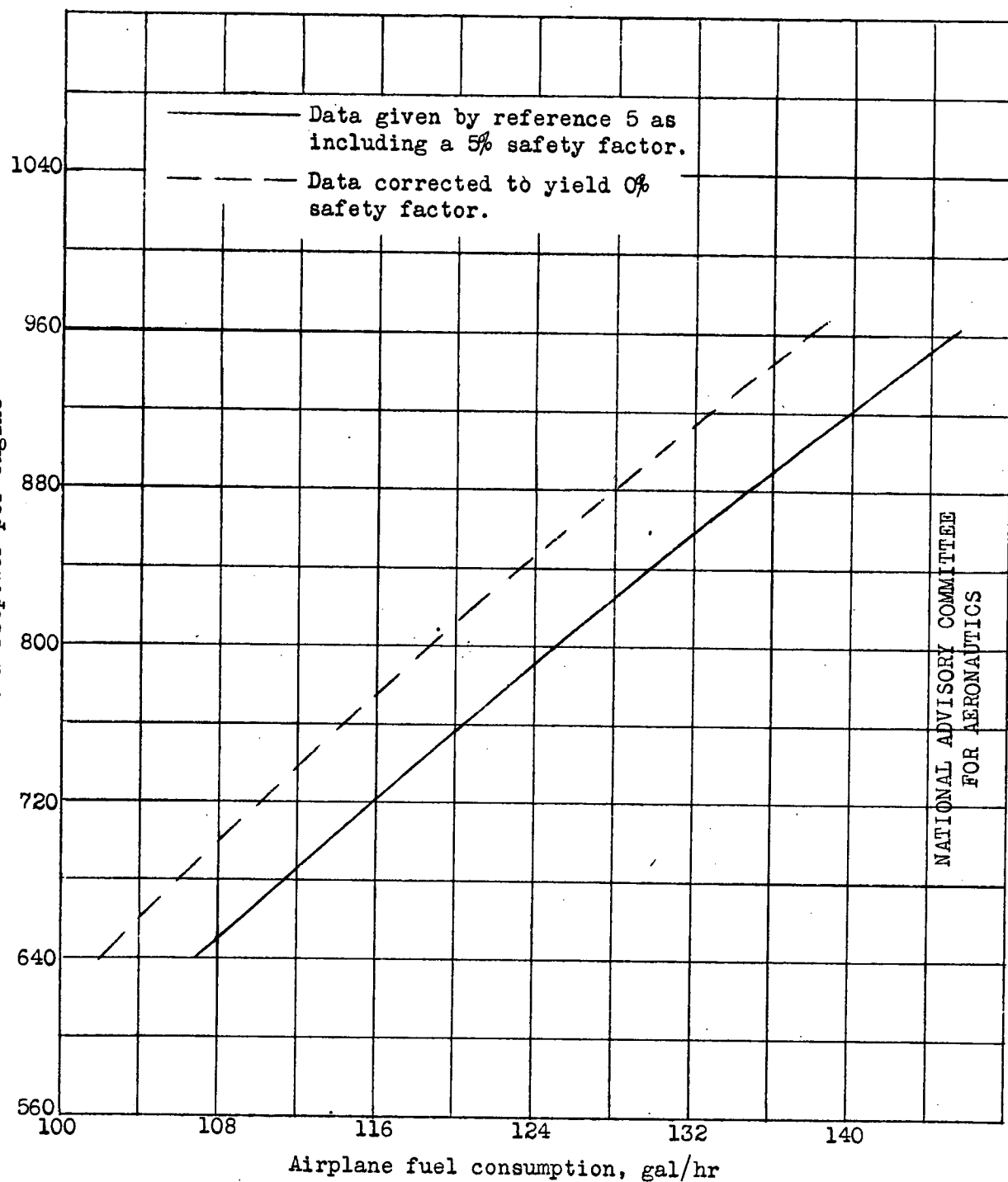   C-46 cargo airplane.

Figure 7.- Variation of fuel consumption with brake horse-
power for 1900 rpm operation of a Curtiss-Wright
C-46 cargo airplane.